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# HIGH REDSHIFT EXTRAGALACTIC ASTRONOMY

# WORKING GROUP REPORT

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## I. Introduction

Our group considered and discussed major scientific opportunities exist for the Millimeter Array in the wide redshift range $z \gtrsim 0.1$. We were assisted in our work be several members of other working groups, whose contributions were particularly important to Sections IID and III below.

We identified three general areas in which the MMA could make major scientific contributions: to Cosmology, to solving questions about the origin of structure in the Universe, and to an exploration of the nature of the 'central engines' of QSOs, radio jets and variable radio sources.

With one exception noted below, the scientific goals we have in mind could be met entirely with continuum observations. Many of the projects we have in mind, however, would be at the limit of the sensitivity of the array. They likewise require a wide range of frequency, but (again with one exception) no particular frequency, so we are free to work where competing foreground sources of emission, like the atmosphere, are at a minimum. In addition, high redshift objects are uniformly distributed, so the latitude of the site for the MMA is not of concern for us.

### II. Cosmology

We begin by discussing scientific goals at the upper end of the redshift range we considered, particularly observations of the cosmic background radiation. To first order this relict of the hot Big Bang is completely isotropic, although large scale anisotropy introduced by the velocity of the solar system has been detected. Our interest is rather with anisotropies on small angular scales. We consider two possible sources of small scale anisotropy, intrinsic fluctuations in the intensity or temperature of the radiation introduced when it last interacted with matter (probably at a redshift $z \simeq 1000$), and small "cool spots" in the radiation introduced by the subsequent inverse Compton scattering of the radiation by hot plasma, especially in clusters of galaxies (the Sunyaev-Zel'dovich effect).

### A. Intrinsic fluctuations

If the matter content of the Universe, or more specifically the baryon content, was inhomogeneously distributed at the time the cosmic background radiation last interacted with it, fluctuations in the temperature of the background will result. Since the Universe is manifestly inhomogeneous now, we expect it was also to some degree inhomogeneous earlier. To produce the presently observed large-scale structure such as galaxies and clusters of galaxies, we expect the fractional density inhomogeneity $\Delta\rho/\rho$ at z $\langle$ 1000 to be roughly $10^{-3}$. The corresponding temperature fluctuations $\Delta T/T$ would be smaller: predicted values range from 3 x $10^{-4}$ to a few times $10^{-6}$ depending on the cosmological model and other astrophysical variables. Whatever their amplitude, detection of intrinsic fluctuations is a vital step in understanding how and when large-scale systems in the Universe formed. Such observations provide the only direct handle on the early history of astronomical systems, permitting us to study them by redshifts several hundred times greater than the redshifts of most distant observed discrete objects. In addition, study of the amplitude and spectrum of such fluctuations may help elucidate some fundamental questions in particle physics, since (1) the relationship between $\Delta\rho$ and $\Delta T$ depends in part on the presence of a cosmologically important density of massive neutrinos, axions or other fundamental particles, and (2) the nature of the mass spectrum $\Delta\rho(M)$ and hence of the spectrum of fluctuations may be determined very early on in the history of the Universe when particle physics was dominant.

Because of their importance, intrinsic fluctuations have been searched for actively. The lowest limit on $\Delta T/T$ is now at just about $10^{-5}$ on scales of 1.5-4.5' (see Figure 1 for comparison with some recent theoretical models). This filled-aperture measurement was made at a wavelength $\lambda = 1.5$ cm, and is close to the state-of-the-art sensitivity for such measurements. Measurements at longer wavelengths, where receiver noise and atmospheric emission present fewer problems, are already running into confusion by faint radio sources. We note that estimates of the radio source confusion suggest that at wavelengths shorter than ~1 cm, confusion will present no problem for observations at a sensitivity ~$10^{-6}$ in $\Delta T/T$. For this reason and others, we believe the MMA offers a powerful tool in the search for intrinsic fluctuations.

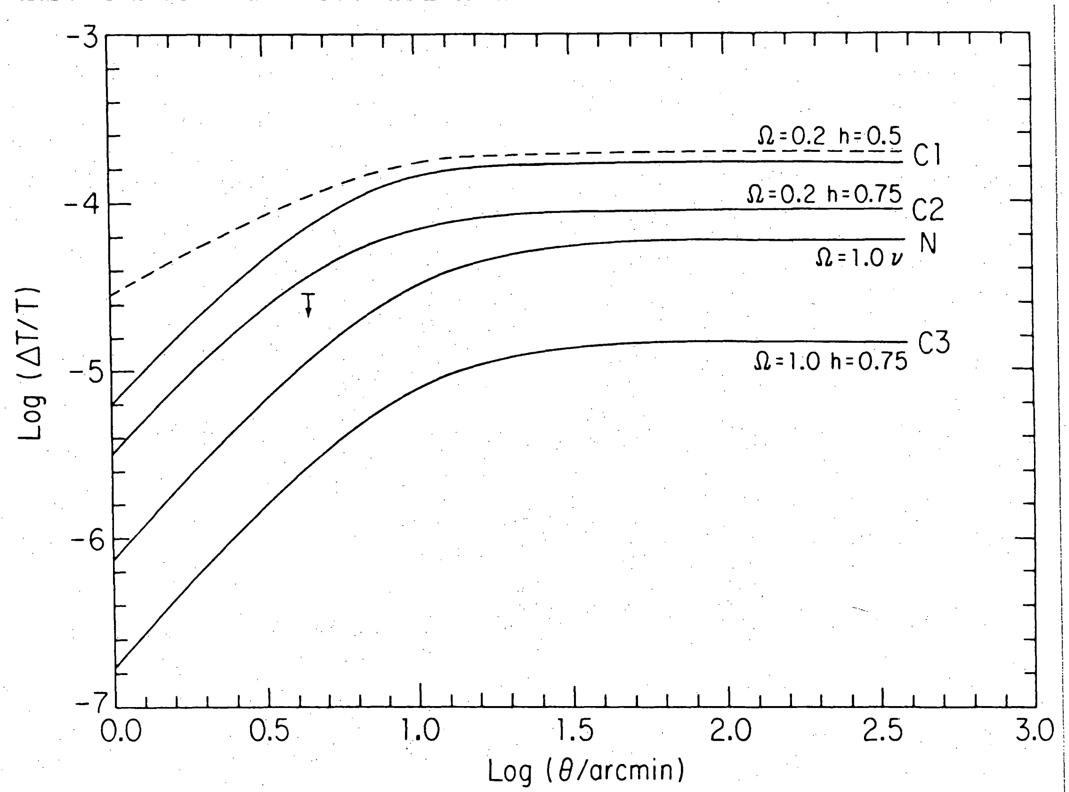


Figure 1. An array of models for intrinsic $\Delta T/T$ fluctuations in the cosmic background radiation, showing the increase in $\Delta T/T$ as $\Theta$ approaches 10'. The single observational limit is by Uson and Wilkinson (Ap. J. 283, 471, 1984). Figure drawn from Bond and Efstathiou, Ap. J. Letters, 285, L45, 1984).

### B. The Sunyaev-Zel'dovich effect

If the cosmic background photons encounter hot plasma, for instance intergalactic plasma in clusters of galaxies, they will be inverse Compton scattered by the electrons of the plasma. This process increases the energy of the photons, but conserves photon number. The effect is to shift an initially blackbody spectrum to higher frequencies, resulting, as shown in Figure 2, in a small temperature decrement, or cool spot in the radiation if it is observed in the Rayleigh-Jeans region through a cluster. (For all $\lambda \gtrsim 1$ mm, the Sunyaev-Zel'dovich produces a temperature decrement.) The magnitude of the effect is directly proportional to the integral of the pressure through the intergalactic plasma, and thus provides a useful diagnostic for plasma properties. Of more general interest is the fact that observations of the Sunyaev-Zel'dovich effect provide a means to measure distances to clusters, distances which are independent of any of the intermediate rungs on the cosmic distance ladder. This possibility arises because the amplitude of the Sunyaev-Zel'dovich effect depends on the parameters of the plasma, but is independent of the distance. On the other hand, the measured X-ray flux from the hot intergalactic plasma does depend on the distance. Observations to date are not sufficiently sensitive to give us good distance estimates even to nearby clusters, and therefore the power of this method in determining the basic cosmological parameter $H_o$ has not yet been utilized. The X-ray measurements necessary to refine our values of $H_o$ should be available within the next decade, thanks to planned space missions. What about the microwave observations? Two problems face us: the contribution of radio sources within the cluster or background sources, and the need to map the cluster so as to obtain information about the distribution of the cluster plasma. The latter requirement is important because the X-ray flux and the Sunyaev-Zel'dovich signal depend on different powers of the plasma density, so that the distribution of hot plasma in the clusters must either be mapped or modeled. The high frequency at which the MMA can operate will help substantially with the first of these two problems. Even in the 30-50 GHz window, we expect to find few sources brighter than 1 mJy. The ability of the MMA to make accurate maps will also help with both problems mentioned above. Sources can be located and excised from the data, and the amplitude of the temperature decrement can be mapped with adequate accuracy. Since the amplitude of the Sunyaev-Zel'dovich effect falls off slowly with distance from the cluster center, the area to be mapped is several times the cluster core radius $R_c$. $R_c$ is typically $\rangle$ 1 arcmin, so regions of $\gtrsim 10'$ extent will need to be mapped at a few arcsecond resolution.

Although the amplitude of the signals expected from typical clusters of galaxies is somewhat higher than the amplitude of intrinsic fluctuations, say $\Delta T/T \simeq$ 1-3 x $10^{-4}$, the effect is still not an easy one to observe, as experience with both filled aperture and interferometric observations has shown. We believe the planned properties of the MMA make it a uniquely powerful instrument to detect and map the Sunyaev-Zel'dovich effect, and thus to provide an independent measurement of $H_o$.

In addition, since the Sunyaev-Zel'dovich effect is independent of distance, we should be able to measure the effect in both nearby and cosmologically distant ($z \simeq 1$) clusters. If the corresponding X-ray measurements can be made, we may then be able to determine $H_o$ at different redshifts, and from these values reduce limits on a second important cosmological quantity, the deceleration parameter $q_o$.

We note here also that the Sunyaev-Zel'dovich effect may arise in other contexts, such as elliptical galaxies that are X-ray sources, and possibly in larger scale structures like superclusters.

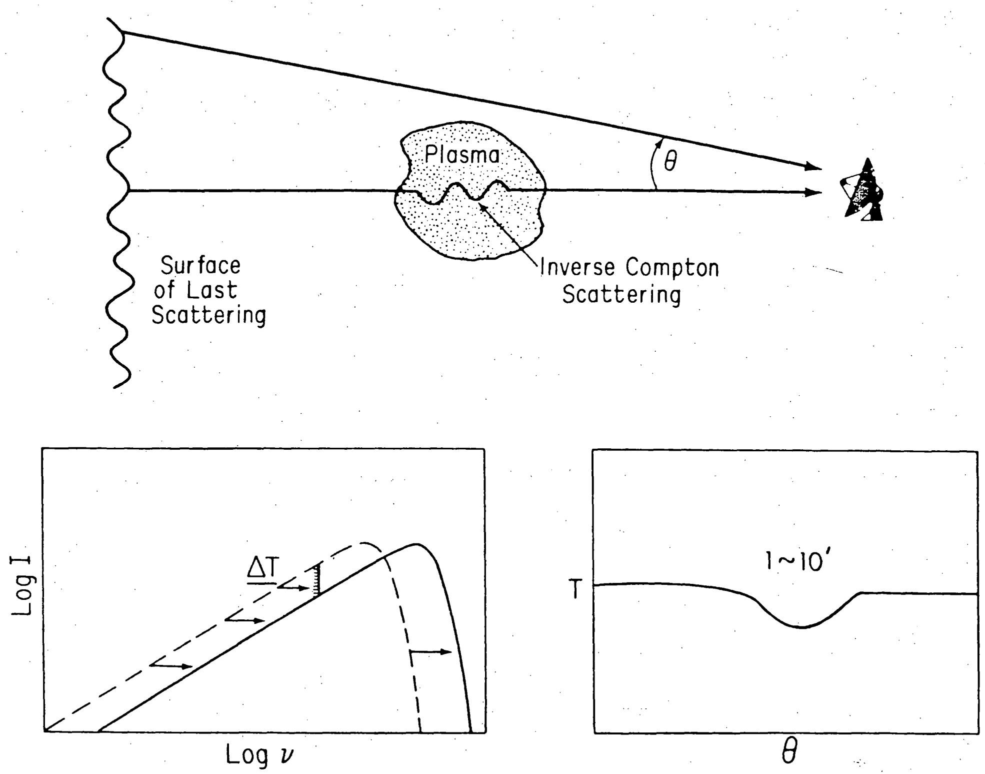


Figure 2. The Sunyaev-Zel'dovich effect produced by the inverse Compton scatterin of cosmic background photons by electrons in the hot intergalactic plasma in clusters of galaxies.

### C. Requirements for the MMA

Both of these experiments will require the highest possible continuum sensitivity. A system temperature of order 50 K and a bandwidth of 1 GHz should be adequate. Because of confusion, wavelengths below 1 cm are favored. Finally, as noted above and in Figure 1, the angular scales at which these effects appear are up to 10'-30'. All of these considerations point in the direction of working at 9 mm as a reasonable compromise. We will make that assumption in the following remarks.

In the search for intrinsic fluctuations on angular scales of ~5' or below, the MMA must provide sensitivity to extended sources. Using the instrument as an interferometer will help avoid some of the systematic error encountered in single dish observations (see below). Nevertheless, a search for fluctuations at the level of a few times $10^{-6}$ in $\Delta T/T$ will require not only high sensitivity, but very careful control of systematic errors. Here we think particularly of antenna or correlator cross talk. In order to make the observations, these systematic effects need to be reduced to a level of a few hundredths of a milliKelvin or below.

As noted above, the interesting angular scale on which to search for intrinsic fluctuations is more like 10'-30'. This scale is larger than any currently planned for the MMA. Our Working Group considered this question at some length and discussed a variety of means of increasing the angular scale of the MMA. The most straightforward such approach was to use 10 meter antennas (or possibly smaller antennas in a central subarray) to make independent measurements of the background temperature of the sky at an array of points spaced by 10'-30' apart. To control atmospheric emission, beam switching would be necessary. If this technique is to be applied, it sets constraints on permissable residual errors in systematic offsets in beam switched operation. Such measurements would not be possible unless the offsets were limited to $\lesssim$0.1 mK, and $\lesssim$ 0.03 mK would be desirable. Such an instrument could then reach the desired sensitivity level of $\Delta T/T \simeq 3 \times 10^{-6}$. To control systematics such as back- and side-lobe pickup, the back-lobe region of the telescopes should be kept clean. In addition, we believe observations of this sensitivity would be precluded by the use of a radome.

Another alternative allowing larger angular scales would be to add to the MMA a tertiary array consisting of even smaller elements, elements small enough to that their primary beam at $\lambda$ = 9 mm would be ~30'. A set of small antennae with diameters less than a meter, or a set of conical horns, are possibilities. We recommend further study of this alternative. Another possibility is adapting the feed elements of the central element to observe the sky directly. Note that small baseline spacings as well as a larger beam are desirable. We believe these questions are thus left to a future engineering study, but we do wish to emphasize that useful observations of intrinsic fluctuations in the cosmic background, and observations of the Sunyaev-Zel'dovich effect in nearby clusters, can be made only if the angular scales to which the instrument is sensitive can be increased by factors of 3-5.

The capabilities of the 'benchmark' instrument we considered for observations of this sort are summarized in Table 1.

### D. Redshifted molecular lines

Another cosmological experiment made possible by the sensitivity of the MMA is a search for molecular lines in absorption at large redshifts. As one instance, note that the 2.6 mm CO line is shifted into the 30-50 GHz band at redshifts of order $z = 2$. Absorption line systems at approximately this redshift have been detected in the optical in some background QSO, and in some cases suggest hydrogen column densities up to $10^{22}$ cm$^{-2}$. Such a high column density suggests that the absorber must be a galaxy (or galaxy halo). It is interesting to ask whether galaxies at such large redshifts contain CO and other molecular species.

We note also that some lines currently inaccessible because of their high frequency, such as the carbon line at 492 GHz, or because of atmospheric blockage, such as the $O_2$ or $H_2O$ lines, may be redshifted into an accessible millimeter band and hence be available for investigation.

## III. Primeval Galaxies

A fundamental problem in astronomy is the origin of galaxies. We have available a range of models for the formation of galaxies, but no direct observations of this process, unlike the situation for stars. That is because galaxy formation occurred in the past. A variety of arguments suggest that most galaxies form their first generation of stars at an epoch corresponding to redshifts $3 \lesssim z \lesssim 30$. The present available upper limits on fluctuations in the cosmic background make the interval $3 \lesssim z \lesssim 10$ more plausible.

Models of primeval galaxies suggest a large energy release during the formation period of order $10^2$-$10^3$ times the present luminosity of galaxies for $10^8$-$10^9$ years. A major component of the luminosity is the emission of massive stars; hence a very high uv flux in the rest frame of the objects is predicted. At $z = 3$-$10$ the uv emission is shifted to the optical. Optical searches for primeval galaxies, however, have failed to find them. There is a natural explanation for this failure: absorption of the uv photons by interstellar dust in the star-forming galaxies. This dust must re-radiate thermally with a peak in the submillimeter region.

Strong support for this basic picture is provided by our best local analogues of primeval galaxies, the star-burst galaxies. These are bright IRAS sources at $\lambda = 100\ \mu$m, and in many cases have spectra still rising at 100 $\mu$m, suggesting a dust temperature $\rangle$ 30 K. Even these local sources are highly luminous–of order 100 Jy at 100 $\mu$m if at a distance of 100 Mpc.

If we adopt these figures, or make projections from models of primeval galaxies, we arrive at the same conclusion: primeval galaxies at $z \simeq$ 3-10 may be detectable at 100-300 GHz using the MMA. The angular scale of the images will be $\rangle$ 5" (depending on the intrinsic properties, z, and cosmological parameters like $H_o$ and $q_o$). The number per square degree also depends on the cosmological parameters, but is large enough (of order 100 deg$^{-2}$) to permit searches for such sources in regions free of other sources. The predicted flux density lies in the range 0.3-30 mJy. Particularly if the flux lies at the lower end of this range, the MMA will have to be pushed to its limits in sensitivity.

The advantages of the MMA over other planned and current instruments are its ability to map a two-dimensional region of the sky at adequate sensitivity, and the greater freedom of millimeter wave observations (compared to submillimeter ones) from emission by Galactic IR cirrus. In addition, a wide range of available frequencies is an advantage, since the peak of thermal dust emission depends on two unknown factors, the redshift of the primeval galaxies and the characteristic temperature of their dust:

$$\lambda_{peak} = \frac{\mathrm{T}}{3(z+1)} mm$$

If these predictions are correct, these dusty primeval galaxies at high redshifts may be the dominant contributors to radio source confusion at $\lambda =$ 1-3 mm.

### IV. The Physics of Radio Sources

We consider here the use of the MMA to map radio sources and also to make high frequency, high sensitivity, and flux density measurements of unresolved sources.

### A. Mapping of radio jets and lobes

An important key to the understanding of radio sources is the ability to map such sources at high frequency. High frequency observations will permit us to study the energetic particles thought to be responsible for the radio emission when they are "younger," that is closer to the time of injection. The characteristic break (change of index) in the radio spectrum of these synchrotron sources occurs at a frequency no related to the age of the radiating particles at $\nu_0 \propto t^{-2}$. Higher frequency observations will thus permit us to look closer at the accelerating "engine" in the cores of these sources. Observations over a wide range of frequencies will permit us to follow the energy loss or aging of the particles in the jets of extragalactic radio sources. MMA maps can thus complement and strengthen VLA results. Such combined observations will increase our understanding of both the physics of the central "engine" of radio sources and of the plasma physics of the jets and lobes themselves.

While the planned-for resolution of the MMA approximately matches that of the VLA, it is known from VLBI observations that radio sources (including jets) have structure on angular scales as small as $10^{-3}$ arcsec. To understand the fine structure of jets, and in particular to investigate conditions near the central "engine" of these sources, higher resolution is needed than is provided for by the "benchmark" instrument we considered. One solution, which we believe requires attention, is to link the MMA to the VLBA, whose antennas will function to 90 GHz at an acceptable efficiency of 25-30%. The combined instrument would permit observations at 3 mm or 9 mm over a range of angular scales of $\sim 10^6$.

To make such a link work, baselines of order 3-30 km are required for the MMA to tie in with the shortest VLBA spacings. In addition, since the center of the VLBA array is at the VLA, and the shortest baselines are centered there, there is a strong argument for siting the MMA near the VLA. This is the one situation we discussed in which we believe a scientific goal dictates a specific location of the MMA.

We also wish to note that long baseline synthesis observations of such sources should be feasible because of the possibility of using self-calibration. Most such sources have one or more bright radio sources present which can be used for self-calibration.

Finally, siting the MMA near the center of the VLBA offers a side benefit–the MMA in its 90 meter configuration could be used on occasion as a phased-array element in the VLBA network itself.

**B. Unresolved sources**

We discussed two classes of unresolved or "point" sources, radio quiet QSO's and variable sources. In both cases, it is the combination of the high frequency response and the high sensitivity of the MMA that opens up new scientific possibilities.

Radio quiet QSO's are those whose radio flux density (at centimeter or longer wavelengths) lies below their optical flux density (some striking examples are shown in Fig. 3). In general, the optical spectra of radio quiet QSO's show an increase in flux as the frequency of observation decreases. Some of these sources were observed by IRAS, which showed that the trend continues to $\lambda = 100\ \mu$m, or $\nu = 3{,}000$ GHz. Where and why does the spectrum break in the radio quiet QSO's? It is observations in the millimeter range which will tell us.

In addition, the central, high luminosity, broad emission line region of these objects is not accessible to radio observations at $\lambda \approx 1$ mm because of free-free opacity. At millimeter (or possibly submillimeter) wavelengths, we may be able to probe the central "engine" of these QSO's as well. The spectral signature of the radio quiet QSO's in the 30-300 GHz range will provide an important diagnostic.

The same may be said for variable radio sources. High frequency observations will detect younger electrons nearer the accelerating region. They may also make possible a bridge between radio variability and optical variability, which in many sources now appear unrelated.

The shorter radiative lifetime in the millimeter region also means that high frequency observations will be less influenced by left-over emission from previous outbursts–a "cleaner" signal will result.

All these considerations, and the expectation of higher fractional variability in the millimeter than in the centimeter region, also make the MMA an attractive instrument for monitoring gravitationally lensed sources. Studies of the variability of lensed sources will provide useful data both on cosmological parameters like $\Omega_0$ and on the properties of the foreground, lensing, and object.

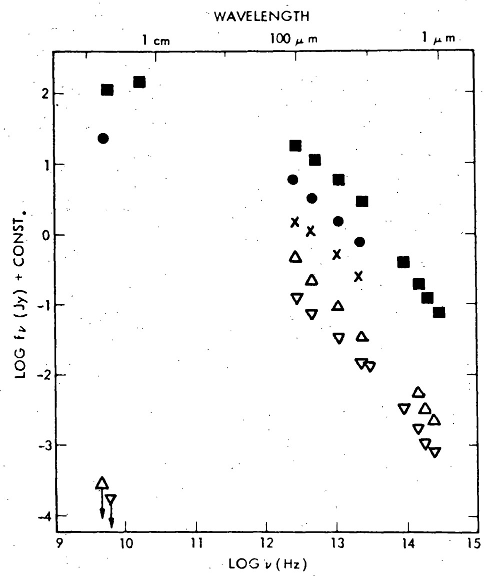


Figure 3. Spectra of radio quiet and radio bright QSO's (from Neugebauer et al. Ap. J. Letters, 278, L83, 1984).

For many of the observations discussed in this section, high frequency is important. On the other hand, because of the intrinsically broad-band nature of the emission mechanisms involved, the gain in moving from the 200-290 GHz atmospheric window to 345 GHz is not vital.

### C. Source Counts

We discussed the use of the MMA to make source counts at millimeter wavelengths. Its high resolution makes it unsuitable for such work. At 9mm our estimates suggest a rapid sky survey with the 10 m antennas used independently would turn up one source every few hours, assuming an integration time per survey area of 1 sec. Sources of S $\gtrsim$ 0.6 Jy could be detected. At $\lambda \lesssim$ 9 mm, the instrument is not useful at all in making source counts –hence out emphasis above on its power to improve our knowledge of known radio sources.

### D. Polarization studies

Many of the kinds of extragalactic radio sources we discussed are polarized, and linear polarization is an important diagnostic of radio-frequency emission mechanisms. If the MMA is to be used usefully to study polarization, the uncertainties in the instrumental polarization of the array need to be reduced to the 0.1% level. The instrumental polarization itself can and probably will be $\gtrsim 0.1\%$, but it must be known, stable and measurable to the 0.1% level.